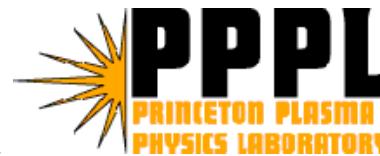

Accelerators for studies of Warm Dense Matter*



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Abstract

We determine requirements on ion beam accelerators needed for the study of warm dense matter physics using ion beams to isochorically heat matter to temperatures of order 1 to 10 eV and at 1% to 100% solid density. We estimate the temperature uniformity of the heated foil, and explore the effects of ion beam velocity spread on the foil temperature uniformity. We describe several accelerator configurations using low to medium mass ions that would lead to the required beam intensity. We show how the technique of neutralized drift compression, combined with final focus optics that are tolerant of large velocity spread can lead to foil temperatures appropriate for the study of warm dense matter physics.

Outline

- I. Requirements -- how can ions be used to study the warm dense matter regime?
- II. Connecting the requirements to accelerator parameters -- what are constraints imposed by basic accelerator physics?
- III. Some accelerator approaches

Basic Requirements

Temperature $T > \sim 1$ eV to study WDM

Energy Density $U \sim 10^{11} - 10^{12}$ J/m³

Pressure $P \sim 1 - 10$ MBar

Strong Coupling Constant $\alpha > \sim 1$

For isochoric heating: Δt must be short enough to avoid cooling from hydrodynamic expansion (to be explained)

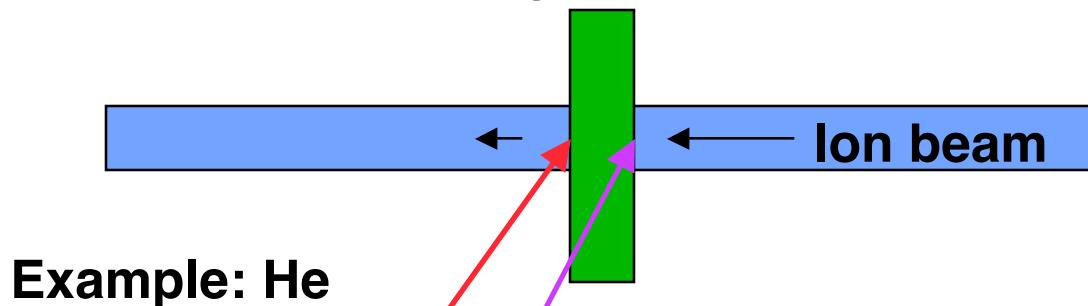
Uniformity: $\Delta T/T < \sim 5\%$ (to distinguish various equations of state)

Timescale for building accelerator: ~ 10 years

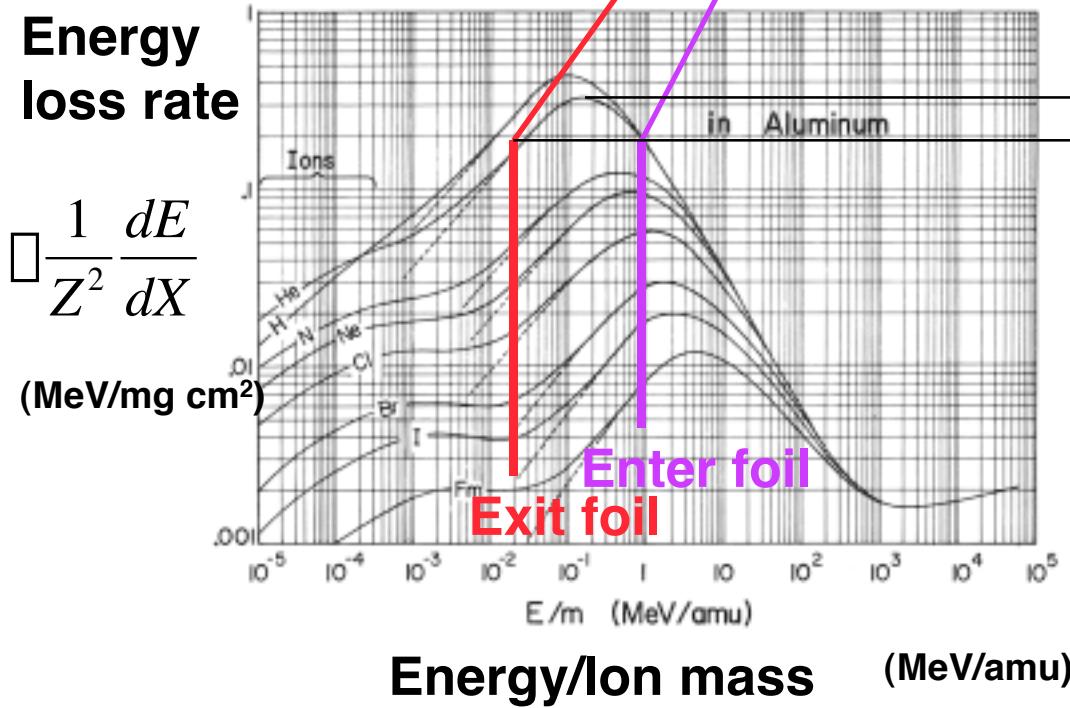


Strategy: maximize uniformity and the efficient use of beam energy by placing center of foil at Bragg peak

In simplest example, target is a foil of solid or “foam” metal



Example: He

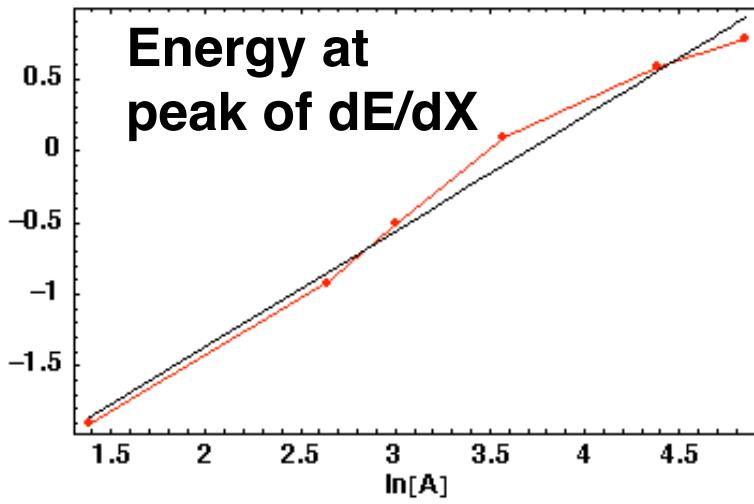
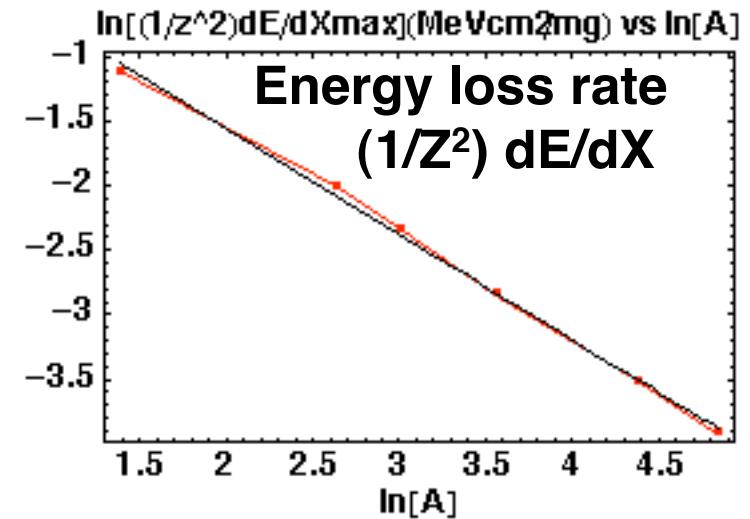
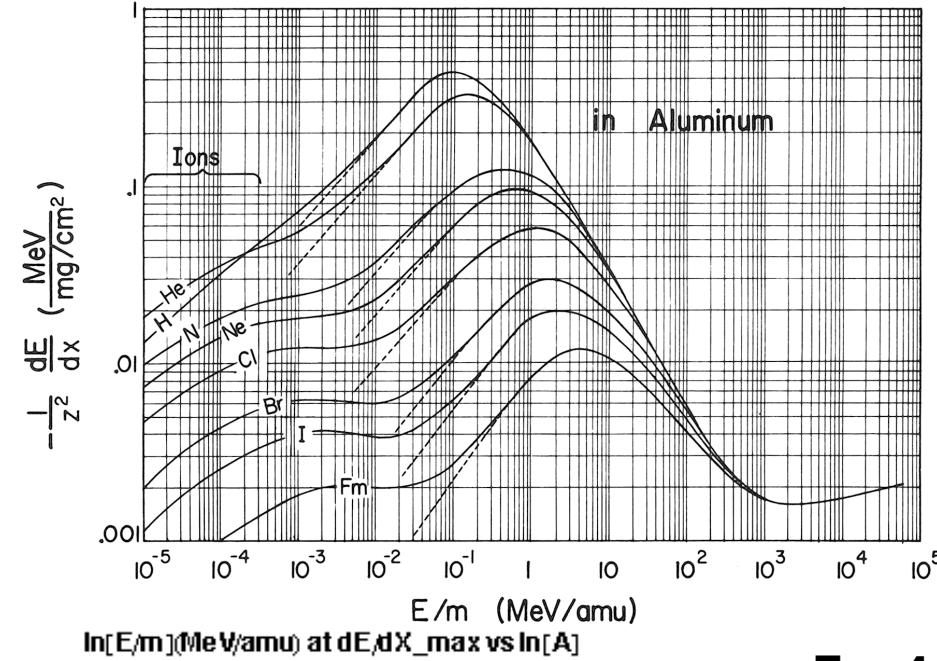


$$\square \frac{dE}{Z^2 dX} \mu \square T$$

log-log plot => fractional energy loss can be high and uniformity also high if operate at Bragg peak (Larry Grisham, PPPL)

(dEdX figure from L.C Northcliffe and R.F.Schilling, Nuclear Data Tables, A7, 233 (1970))

Increasing ion mass, increases energy of Bragg peak, and energy loss rate at Bragg peak



For $4 < A < 126$ (He \rightarrow I):

Energy at maximum dE/dX :

$$E_{dEdX_{max}} \sim 0.052 \text{ MeV } A^{1.803}$$

Energy loss rate at maximum dE/dX :

$$(1/Z^2)dE/dX_{max} \sim 1.09 \text{ (MeVcm}^2/\text{mg}) A^{-0.82}$$

$$dE/dX_{max} \sim 0.35 \text{ (MeVcm}^2/\text{mg}) A^{1.07}$$

Some scalings

$$E \text{ (at } dE/dX_{max}) = \sim 0.052 \text{ MeV } A^{1.803}$$

$\Delta E/E = \sim < 0.50$ **(for a 5% change in dE/dX , half width in energy)**

$$Z = 2\Delta E/(\Delta dE/dX) = \sim (0.55-0.77) \propto A^{0.733} (\Delta_{al}/\Delta) \quad \text{(width of foil for 5% change)}$$

Energy density increases with higher ρ , larger A :

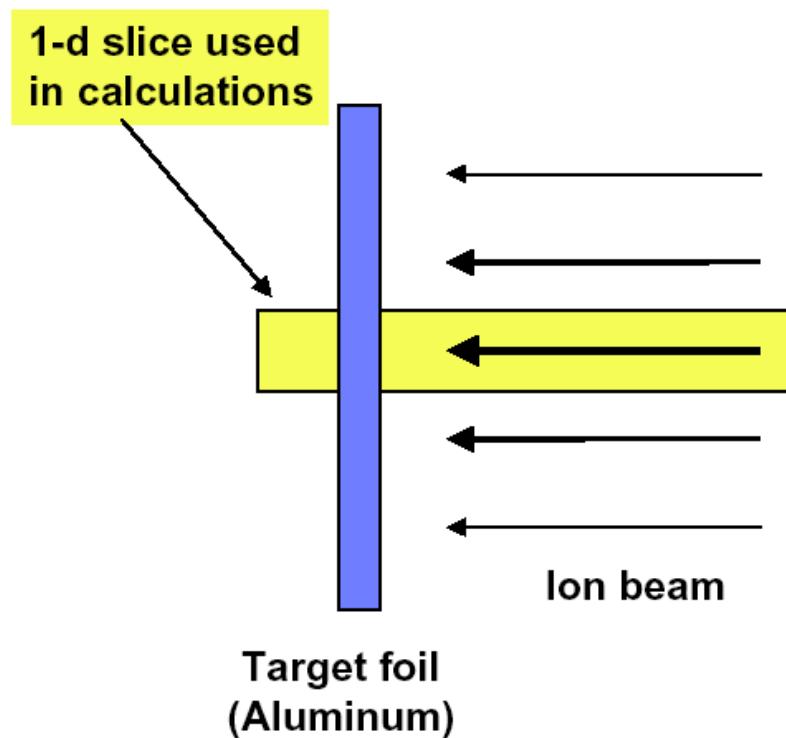
$$U = \frac{N_{ions} E}{\rho r^2 Z} = 3.7 \times 10^9 \frac{\text{J}}{\text{m}^3} \frac{N_{ions}}{10^{12}} \frac{1}{r} \frac{\text{mm}^2}{\Delta_{al}} A^{1.07}$$

Hydro time increases with lower ρ , and weakly on larger A :

$$t_{hydro} = Z/c_s = \frac{Z}{\sqrt{\rho U}} = 0.6 \times 10^{10} \text{s} \frac{10^{12}}{N_{ions}}^{1/2} \frac{1}{r} \frac{\text{mm}^2}{\Delta_{al}} A^{0.198}$$

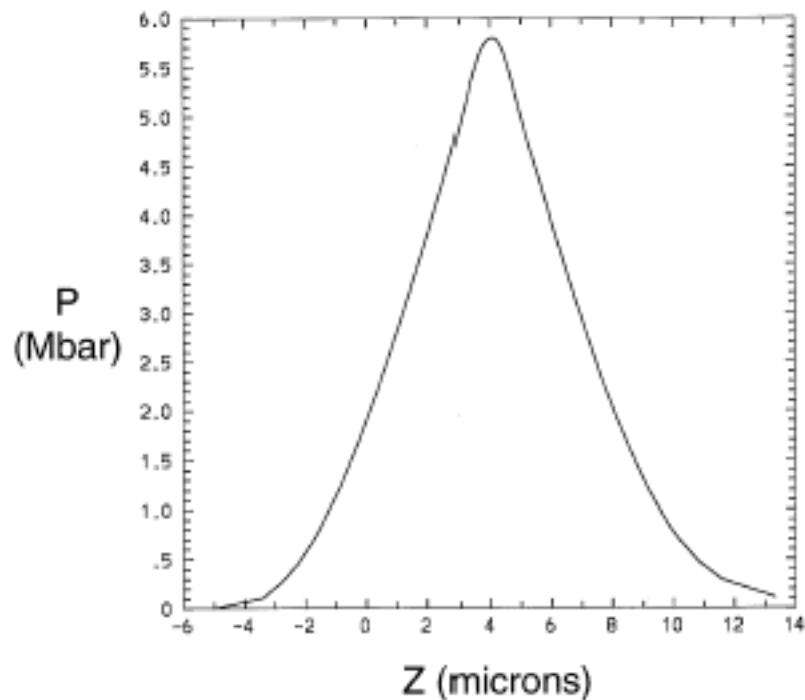
Simulations were carried out by D. Callahan, to explore hydrodynamic effects

- 1-d calculations for the center of the beam
 - Assuming a 1 mm radius Gaussian beam, used 2% of the energy in a 100 micron radius spot
 - 2-d and 3-d effects will make the target expand faster
- “2015” machine
 - Ne^{+1} ion
 - 30 MeV kinetic energy
 - 1 mm radius at best focus
 - 0.5 ns pulse duration
 - 30 J total beam energy
 - 20 - 40 MeV energy spread
 - 60 GW power
 - 3.8 TW/cm^2 center of beam

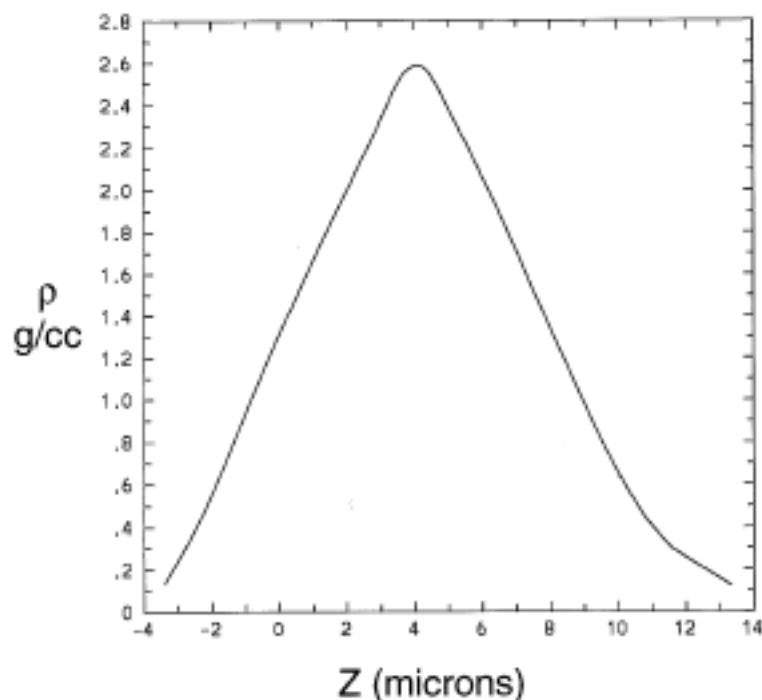


For a 8 μ target, the target has expanded and is non-uniform

Pressure at 0.27 ns



Density at 0.27 ns



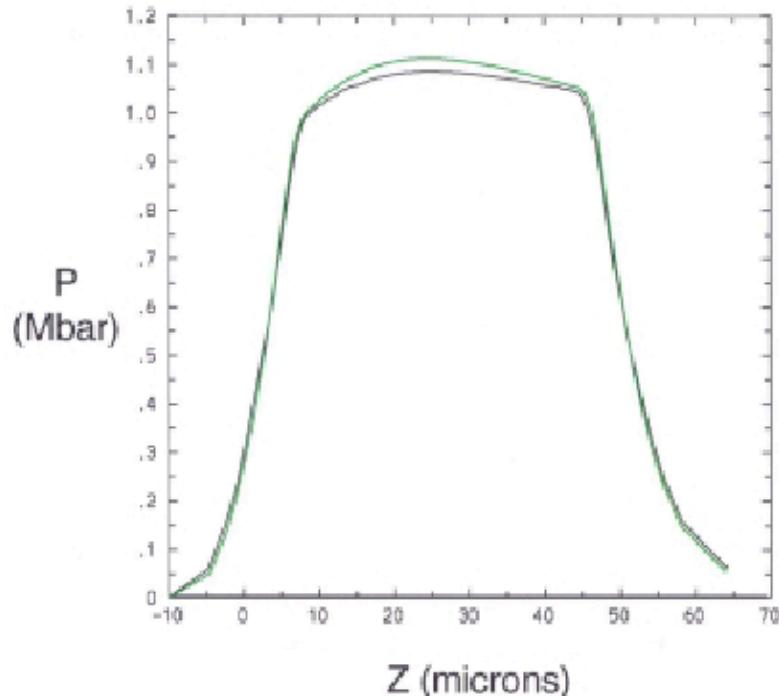
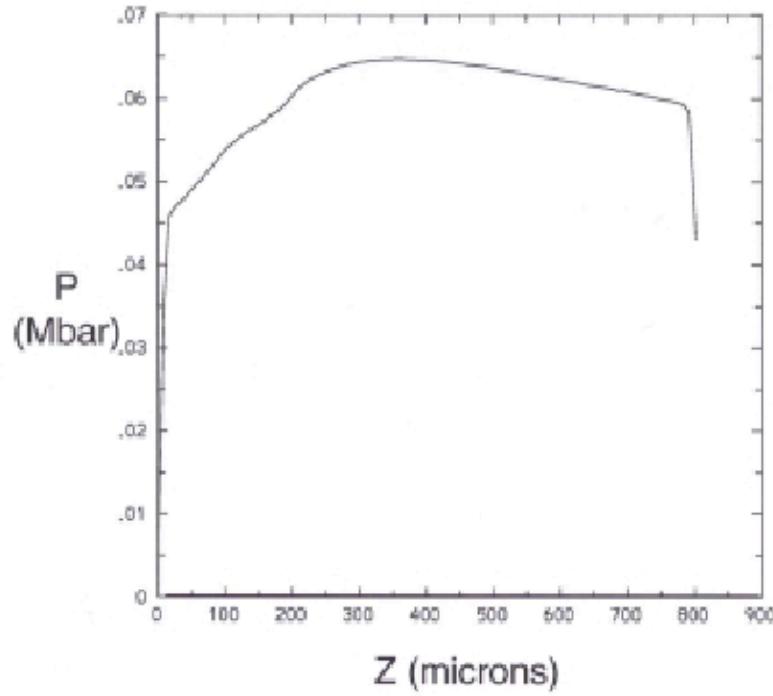
Target was initially 8 microns thick at 2.7 g/cc

(slide courtesy D. Callahan and Max Tabak, LLNL)

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Using a low density target with the “2015” machine results in more uniformity, but less energy density



1% solid density
800 microns thick

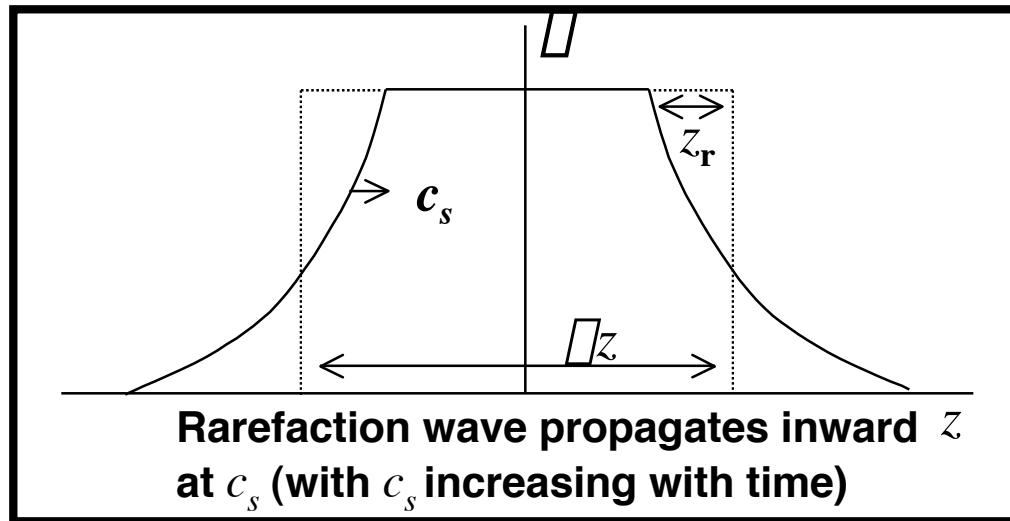
15% solid density
53 microns thick

(slide courtesy D. Callahan and M. Tabak, LLNL)

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For larger targets ($\Delta z > \Delta z_{\min} \sim 40 \mu$), pulse duration can be significantly longer



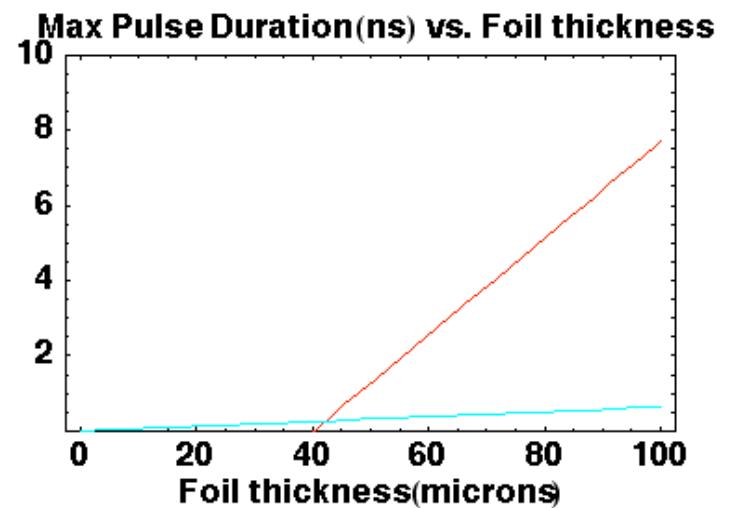
Δz_{\min} is the minimum length in z for which diagnostics may interrogate the region of interest. We assume $\Delta z_{\min} = 40 \mu$ in this example.

$$\frac{\Delta t}{\Delta z} = \frac{(\Delta z - \Delta z_{\min})}{2(2c_s^*/3)}$$

for $\Delta z > \Delta z_{\min}$

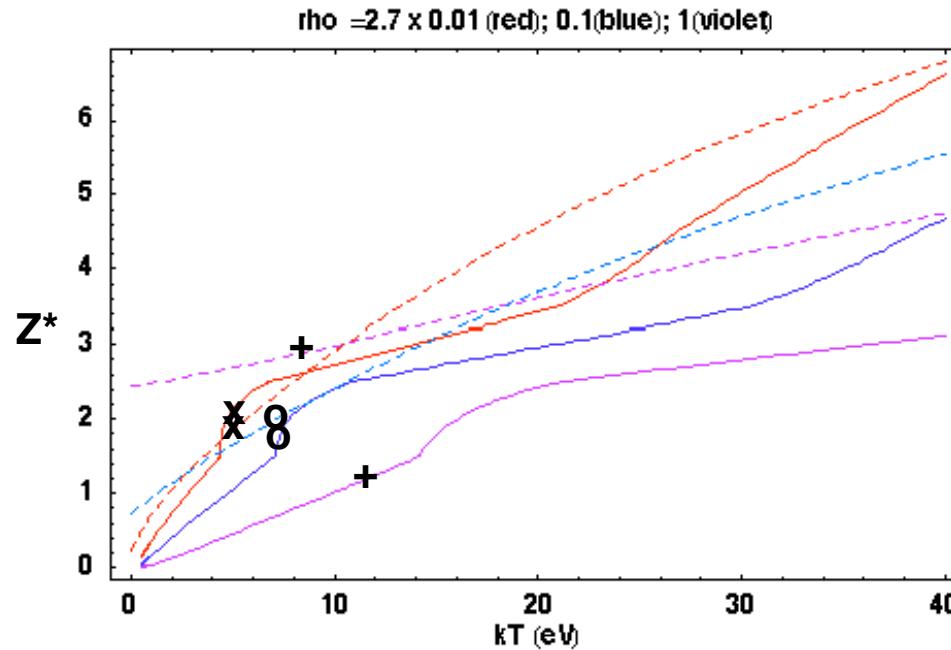
$$\frac{\Delta t}{\Delta z} = \frac{2(20)(2c_s^*/3)}{2(20)(2c_s^*/3)}$$

for $\Delta z < \Delta z_{\min}$



Two simple models for equation of state and ionization state Z^* differ in predictions

$\rho/\rho_{\text{solid}} = 0.01$ (red);
0.1 (blue);
0.01 (violet)



Model = Approximate Saha Equation (Zeldovitch-Raiser) **Solid**
or Thomas-Fermi Model (Kemp, 1988, Atzeni & Meyer-ter-Vehn, 2003) **Dashed**

Accelerator example using Ne^{+1} (see next slide):
 $x: \rho = .027; U = .045 \times 10^{11}$ ($\rho = 1.7 \times 10^{12} \text{ erg/gm}$)
 $o: \rho = 0.27; U = .45 \times 10^{11}$ ($\rho = 1.7 \times 10^{12} \text{ erg/gm}$)
 $+: \rho = 2.7; U = 4.5 \times 10^{11}$ ($\rho = 1.7 \times 10^{12} \text{ erg/gm}$)

Note that for Al: Melting point= 933 K=0.08 eV; Boiling point=2793 K = 0.24 eV

Example parameters: Ne⁺¹ beam

Ne: Z=10, A=20.17, E_{min}=7.7 MeV, E_{center}=12.1 MeV, E_{max}=20.1 MeV
z_{min} = 40

ρ(g/cm ³)(%solid)	0.027 (1%)			0.27 (10%)			2.7 (100%)		
Foil length (μ)	480			48			4.8		
kT (eV)	3.1	4.8	15	4.2	7.3	18	5.9	12	22
ρ	1.1	2.1	2.7	0.56	1.7	2.6	0.56	1.2	2.5
U _{ii} =Z* ² e ² n _i ^{1/3} /kT	0.45	1.1	0.95	0.30	0.63	1.4	0.30	0.70	1.6
N _{ions} /(r _{spot} /1mm) ² /10 ¹²	1	3	10	1	3	10	1	3	10
t (ns)	84	48	27	3.8	2.2	1.2	0.04	0.03	.014
U (J/m ³)/10 ¹¹	.015	.045	0.15	0.15	0.45	1.5	1.5	4.5	15

(Eq. of state, Z*: Zeldovich and Raizer model from R.J. Harrach and F. J. Rogers, J. Appl. Phys. **52**, 5592, (1981).)



Example parameters: Cl⁺¹ beam

Cl: Z=17, A=35.453, E_{min}=21.1 MeV, E_{center}=48.8 MeV, E_{max}=68.5 MeV
 z_{min} = 40

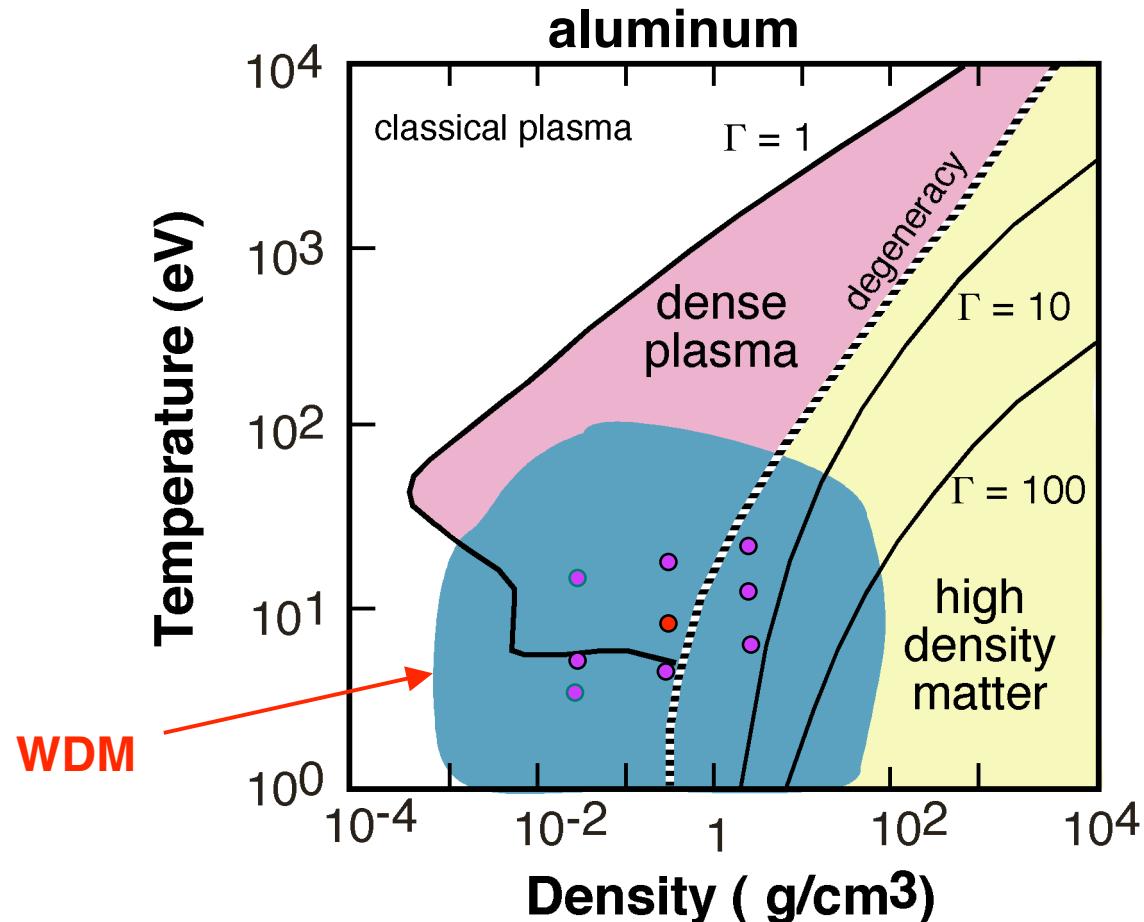
ρ (g/cm ³)(%solid)	0.027 (1%)			0.27 (10%)			2.7 (100%)		
Foil length (μ)	1050			105			10.5		
kT (eV)	3.8	6.5	20	5.2	8.5	25	7.6	14	31
ρ	1.3	2.5	3.5	1.1	2.2	3.2	0.75	1.5	2.8
$\Omega_{ii} = Z^* e^2 n_i^{1/3} / kT$	0.45	1.1	0.71	0.61	1.5	1.1	0.42	0.77	1.5
$N_{ions} / (r_{spot}/1mm)^2 / 10^{12}$	1	3	10	1	3	10	1	3	10
Ωt (ns)	96	56	30	6.2	3.5	2.0	0.050	0.028	.012
U (J/m ³)/10 ¹¹	.022	.065	0.22	0.22	0.65	2.2	2.2	6.5	22

(Eq. of state, Z*: Zeldovich and Raizer model from R.J. Harrach and F. J. Rogers, J. Appl. Phys. **52**, 5592, (1981).)

Defining the Warm Dense Matter regime

WDM is that region in temperature (T) - density (Γ) space:

- 1) Not described as normal condensed matter, i.e., $T \sim 0$
- 2) Not described by weakly coupled plasma theory



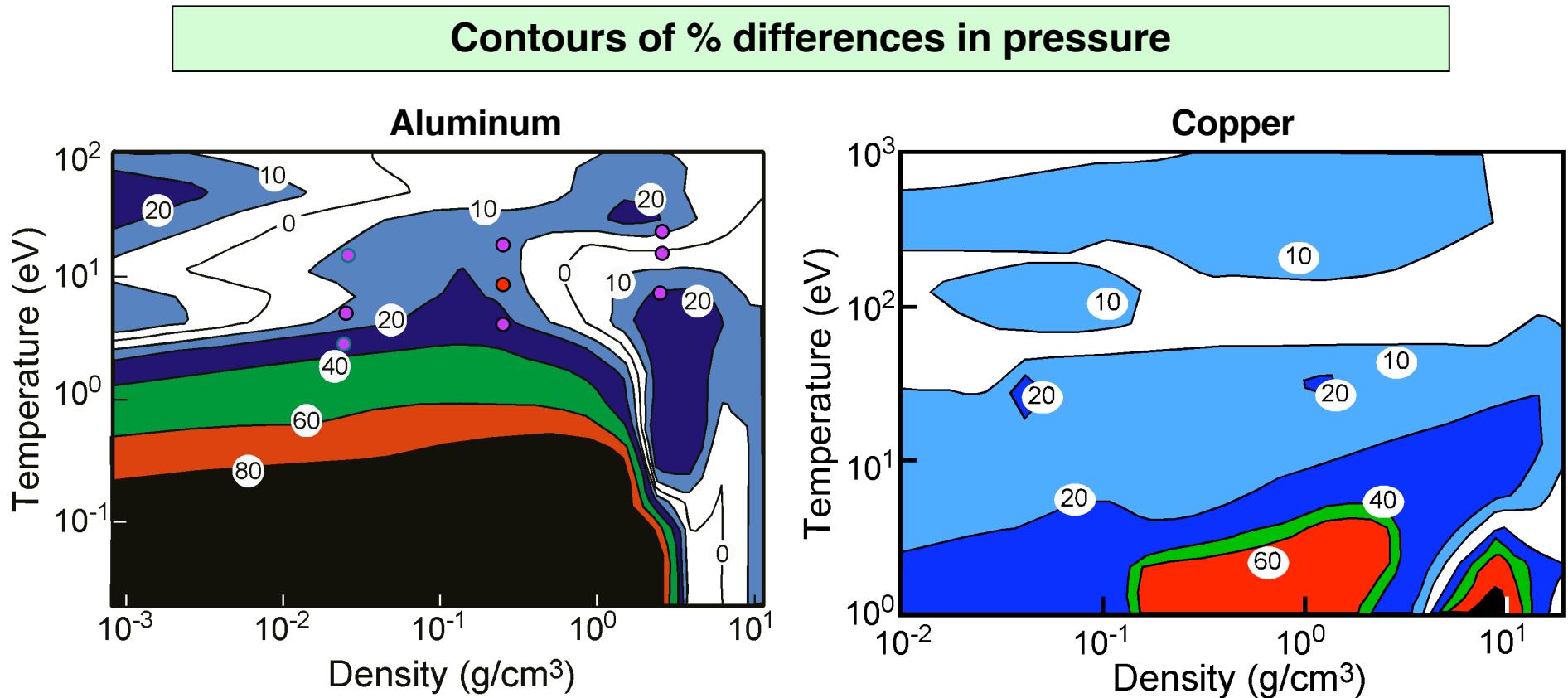
- Γ is the strong coupling parameter, the ratio of the interaction energy between the particles, V_{ii} , to the kinetic energy, T

- $$\Gamma = \frac{V_{ii}}{T} = \frac{Z^2 e^2}{r_o T}$$

where $r_o = \frac{1}{\Gamma^{1/3}}$

(slide courtesy R. Lee, LLNL)

In Warm Dense Matter regime large errors exist even for most studied materials (slide courtesy R. Lee, LLNL)



- EOS Differences $> 80\%$ are common
- Measurements are *essential* for guidance
- Where there is data the models agree!!
 - Data is along the Hugoniot - single shock \square -T-P response curve

Accelerator to achieve WDM is challenging -- explores new beam physics regimes

Consider:

20 MeV Ne⁺ beam, $\Delta t = 1 \text{ ns}$, $N_{ions} = 1.0 \times 10^{13}$ particles

Then:

$\gamma \sim 0.045$;

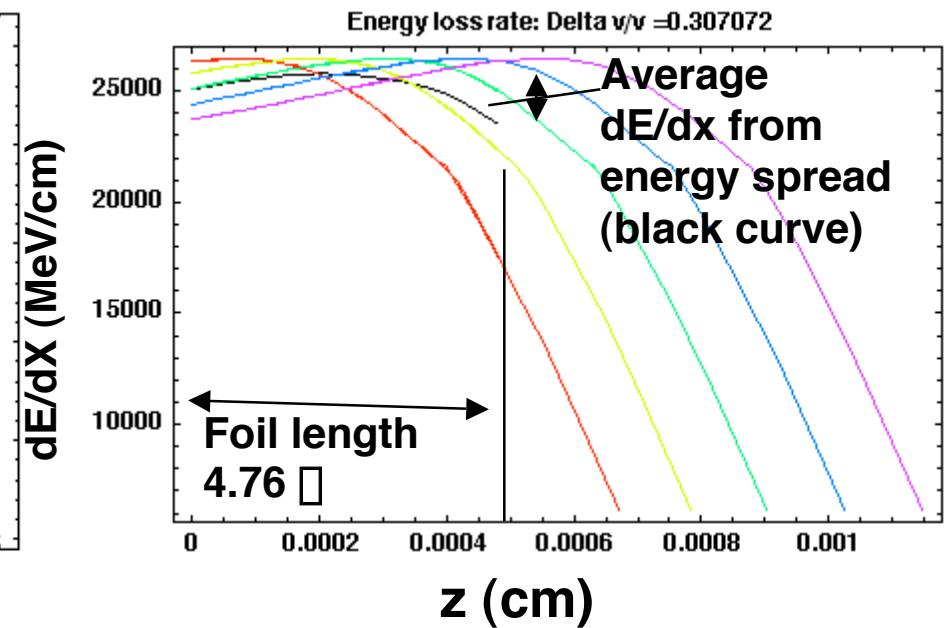
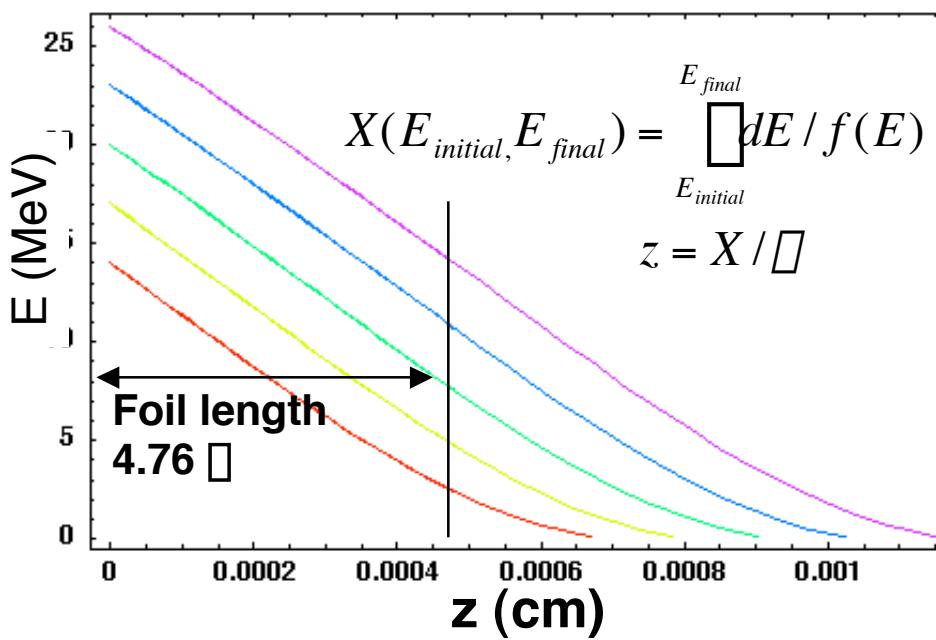
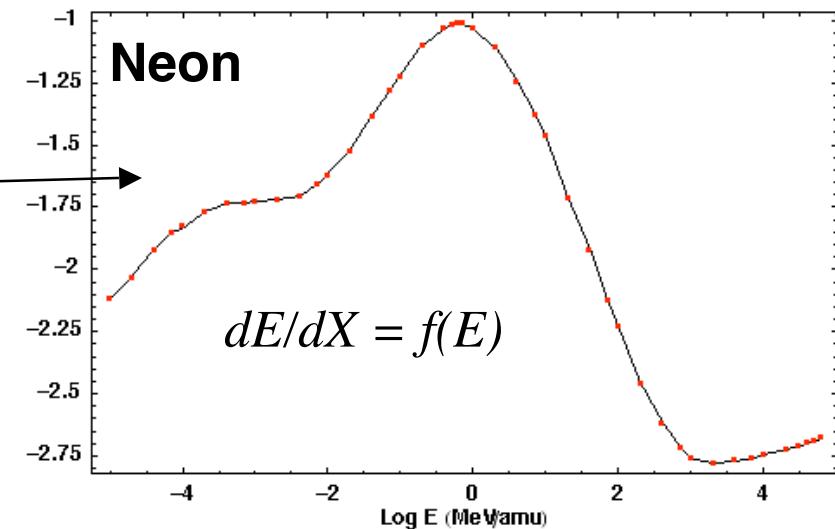
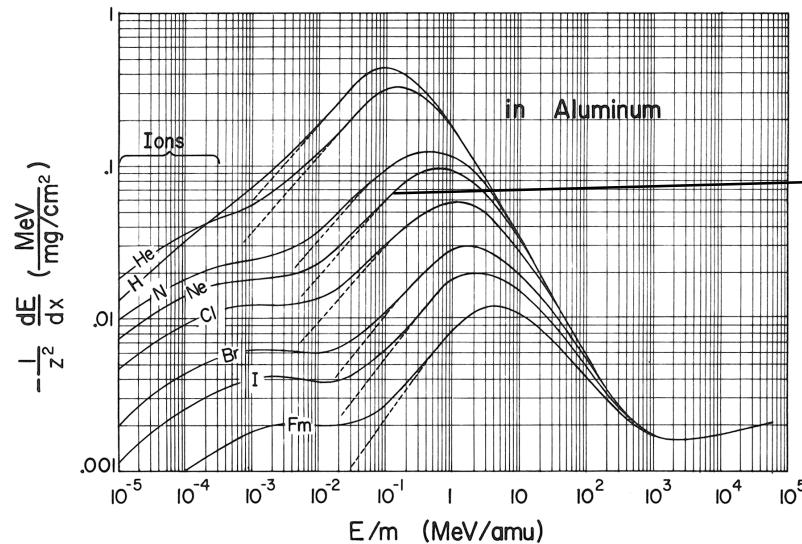
Bunch length $l_b = \gamma c \Delta t = 1.4 \text{ cm}$

Line charge = $eN_{ions}/l_b = 110 \text{ nC/m}$

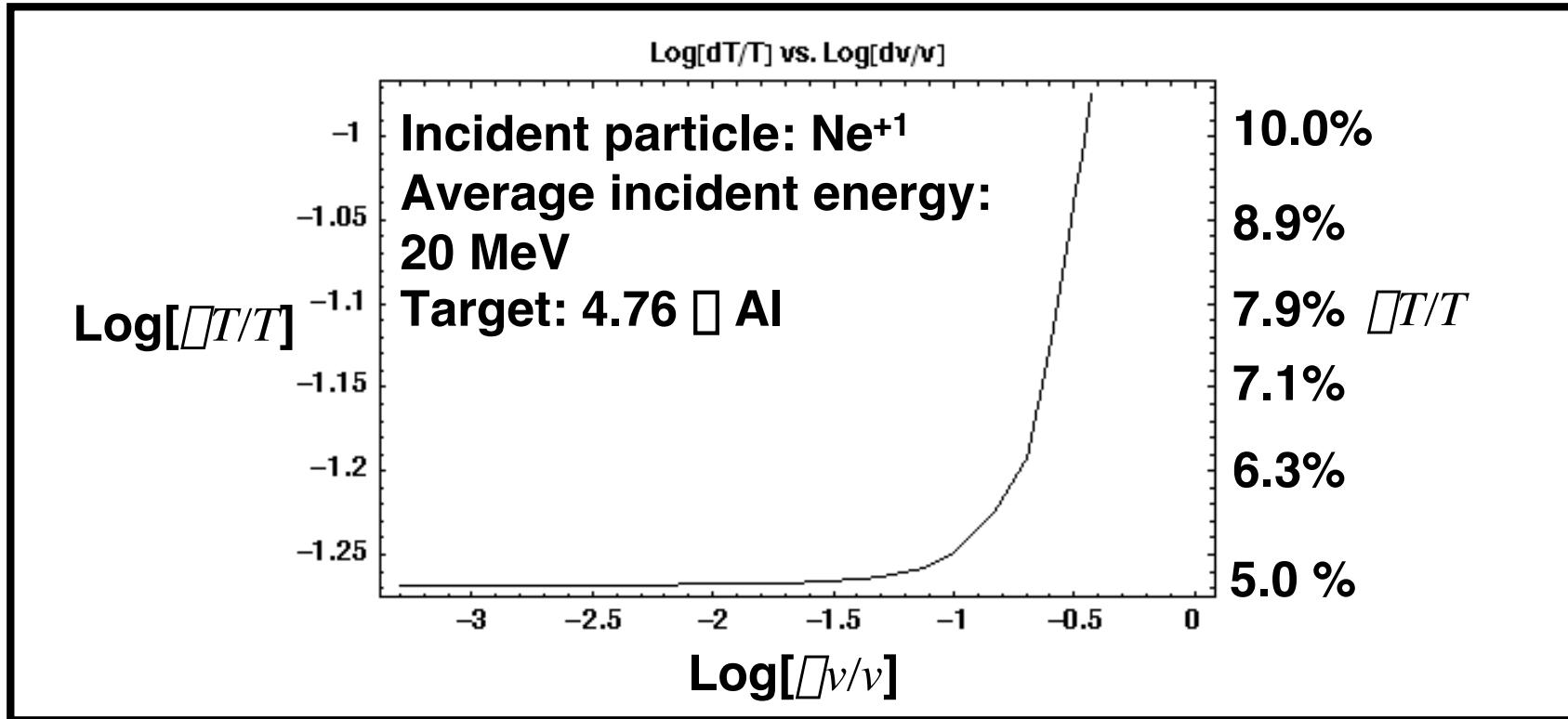
$E_z \sim eN_{ions}/4\pi\epsilon_0 l_b^2 \sim 75 \text{ MV/m}$

So just to keep beam together requires substantial electric field. (1-2 MV/m typical “limit” in induction linac). So instead: use plasma to neutralize beam during final focus and drift compression

The effect of a velocity spread on temperature uniformity on target can be examined



Log $\Delta T/T$ vs. Log $\Delta v/v$



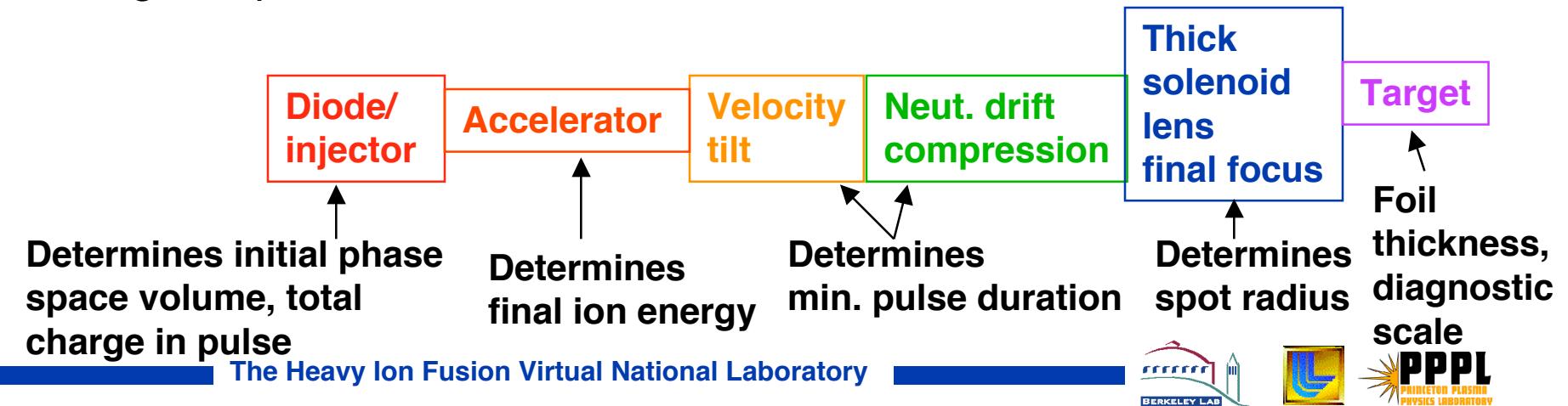
For a uniform distribution of energies, velocity spread $\Delta v/v$ does not reduce temperature spread. But as long as velocity spread $\sim 10\%$, temperature spread not significantly increased either.
General result: if $\Delta E_{\text{spread}} \sim \Delta E_{\text{single particle}}$ then spread does no harm.

How do you connect the requirements to achievable parameters?

What ion mass, charge, and energy to choose?

1. Source/ Injector
2. Accelerator
3. Drift compression
4. Final focus
5. Target experiment

Consider simple model:



Source/ Injector

a). Beam quality

1. Transverse emittance

$$\text{Q}_N = 2r_b(kT/mc^2)^{1/2} = 0.051 \text{ mm-mrad } (r_b/0.25\text{cm}) (20.1/A)^{1/2} (kT/2 \text{ eV})^{1/2}$$

To avoid voltage breakdown $d=.01 \text{ m } (V_d/100 \text{ kV})^2 (100 \text{ kV}/V_b)^2$

$$\Rightarrow Q_f = 1.4 \text{ mm-mrad } (4/\square) (kT_s/2 \text{ eV})(V_d/100 \text{ kV})^2(100 \text{ kV}/V_b)^2(12 \text{ MeV}/qV_f)^{1/2}$$

b). Current $I = (4\square r_b/9) (2q/m)^{1/2} (V_d^{3/2}/\square^2)$ Here $\square = d/r_b \sim 2.5 - 8 = 4$
 $= 0.0745 \text{ A } (20.1/A/q)^{1/2} (4/\square)^2 (V_d/100 \text{ kV})^{3/2}$

-- Total charge $I\square t = 15 \text{ nC } (20.1/A/q)^{1/2} (4/\square)^2 (V_d/100 \text{ kV})^{3/2} (\square t/200\text{ns})$

-- Pulse energy $V_f I \square t = 0.18 \text{ J } (20.1/A/q)^{1/2} (4/\square)^2 x (V_d/100 \text{ kV})^{3/2} (\square t/200\text{ns})(V_f/12\text{MV})$

Neutralized drift compression allows possibility of very short pulses

For a parabolic pulse the longitudinal envelope equation (including longitudinal thermal spread) for bunch length l is:

$$\frac{d^2l}{dt^2} = \frac{16\zeta^2}{l^3} + \frac{4v_0^2 g Q_a l_a}{l^2} \quad || \quad \frac{\Box v}{\Box v_{tilt}}^2 = \frac{1}{v} \frac{dl}{dt} \Big|_a^2 = 20 \frac{\Box v}{\Box v_a}^2 [C^2 \Box 1] + 8gQ_a [C \Box 1]$$

Thermal Space
Spread Charge

$$\text{where } \zeta^2 \equiv 25 \left(\langle \Box v_z^2 \rangle \langle \Box k^2 \rangle - \langle \Box v_z \Box k \rangle^2 \right)$$

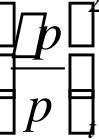
So if velocity spread at end of accelerator $\Box v/v_a \sim 5 \times 10^{-4}$, (corresponding to say an error in voltage $\Box V/V \sim 0.1\%$ during imposition of velocity tilt), an initial tilt $\Box v/v \sim 1$, and perveance in drift section $Q_a = \sim 0$:

$$C_{\max} = \frac{\Box [\Box v/v]_{tilt}^2}{20[\Box v/v]_a^2} + 1^{1/2} \\ \Box \frac{\Box v/v_{tilt}}{4.5 \Box v/v_a}$$

(example: $\Box v/v_{tilt} = 1$, $\Box v/v_a = 5 \times 10^{-4}$,
 $\implies C_{\max} = 450$)

Drift compression and final focus through a thick solenoidal lens

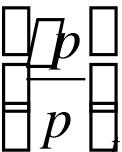
If $r_{spot}^2 = \frac{4\beta f^2}{\beta^2 r_0^2} + \frac{\beta^2 r_0^2}{4} \frac{p^2}{p^2}$



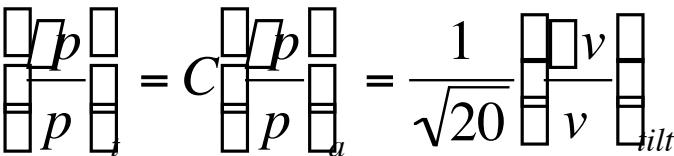
then optimum initial beam radius r_{0_opt}
which minimizes r_{spot} :

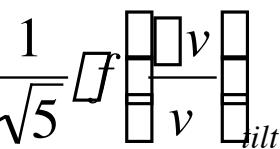
$$r_{0_opt}^2 = \frac{4\beta f}{\beta^2 (\beta p / p)_t}$$

Minimum spot radius at r_{0_opt} is then:

$$r_{spot \min}^2 = 2\beta f \frac{p^2}{p^2}$$


At maximum compression

$$\frac{p^2}{p^2} = C \frac{p^2}{p^2} = \frac{1}{\sqrt{20}} \frac{v^2}{v^2}_{tilt}$$


$$r_{spot \ min}^2 = \frac{1}{\sqrt{5}} \beta f \frac{v^2}{v^2}_{tilt}$$


Example: for $\beta v/v_{tilt} = .2$, $\beta = 1.4$ mm-mrad,
 $f=0.5$ m, $\Rightarrow r_{spot \ min} = 0.25$ mm

Use: $\beta_N = 2r_b(kT/mc^2)^{1/2}$, $\beta = \beta_N/\beta_p$ and $r_b = d/\beta$, and
 $d = .01$ m $(V_d/100$ kV) 2 $(100$ kV/ V_b) 2

$\Rightarrow \beta = 1.4$ mm-mrad $(4/\beta) (kT_s/2.0$ eV) $(V_d/100$ kV) 2 $(100$ kV/ V_b) 2 $(12$ MeV/ qV_f) $^{1/2}$

Target requirements for HEDP

Target thickness for 5% temperature variation:

$$Lz = 5.0 \frac{A}{20.1}^{0.733} \frac{al}{20.1}$$

Final accelerator voltage (at Bragg peak):

$$qV_f(\text{at } dE/dX_{max}) = \sim 0.052 \text{ MeV } A^{1.803}$$

Target energy density U :

$$U = V_f I_d L t_d / (r_{spot}^2 L z)$$

$$= \frac{I_d L t_d V_f}{(0.25 \text{ mm})^2 f v/v_{tilt} 4 V_d^{3/2} T_s^{1/2} 12 \text{ MeV}^{1/2} 5.0 \frac{A}{20.1}^{0.733} \frac{al}{20.1}} = \frac{0.18 J}{0.5 \text{ m}^{1/2} 0.2^{1/2} 100 \text{ kV}^{1/2} 100 \text{ kV}^{1/2} 2.0 \text{ eV}^{1/2} qV_f^{1/2} L z}$$

$$U = 1.8 \times 10^{11} \frac{J}{\text{m}^3} \frac{2 \text{ eV}^{1/2}}{kT_s} \frac{0.2}{v/v_{tilt}}^{0.32} \frac{4}{1}^{0.32} \frac{L t_d}{200 \text{ ns}} \frac{V_b}{100 \text{ kV}}^{1/2} \frac{V_d}{100 \text{ kV}}^{1/2} \frac{V_f}{12 \text{ MV}}^{0.50} \frac{0.5 \text{ m}}{f}^{0.815} \frac{al}{20.1}$$

Timescales

Pulse duration

$$\boxed{t_t} = \boxed{t_d} / C = 2.25\text{ns}$$

Hydro expansion $\sim \boxed{z}/(\boxed{U})^{1/2}$

$$t_{hydro} = 0.6\text{ns}$$

Ratio: t_{hydro}/\boxed{t}_t **must be** $\gg 1$

$$\frac{t_{hydro}}{\boxed{t}_t} = 0.27$$

Note that t_{hydro}/\boxed{t}_t **and** U **depend only on ratio of** $\boxed{v/v_{tilt}}/\boxed{t}_d$, **so lower velocity tilts with smaller diode pulse durations achieve same** t_{hydro}/\boxed{t}_t , **and** U **but with smaller** r_{spot} **to go along with small pulse energy.**

We have begun studying a number of accelerator concepts to achieve WDM

A recent workshop held at LBNL (September 26-29), together with ongoing “brainstorming” meetings at LBNL (since May 2004) have spurred development of a number of concepts for ion-driven WDM accelerators:

1. rf:

- a. Multi-beam, interdigital H-mode cavities drift tube linac, 50 MHz (3 different beam configurations), solenoidal focusing
- b. Single beam, interdigital H-mode cavities drift tube linac, with storage ring, solenoidal focusing

2. Pulsed power: multigap

- a. Broad-Band Traveling Wave Accelerator
- b. Multi-beam pulsed drift tube linac, electrostatic focusing
- c. Multi-gap induction cores
- d. High gradient induction

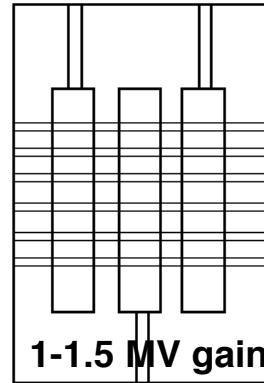
3. Pulsed power: single gap

- a. Existing light ion diodes at NRL or SNL
- b. Ionization front accelerator

rf approach (concept 1a): multiple beamlines focused with a strong multi-channel solenoid, and accelerated by an H-mode drift tube

Interdigital H-mode cavity

25 cm



Interdigital H-mode cavity

Multi-channel Solenoid

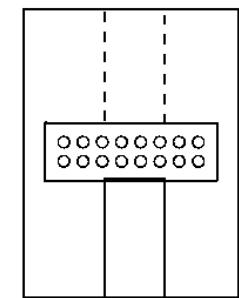
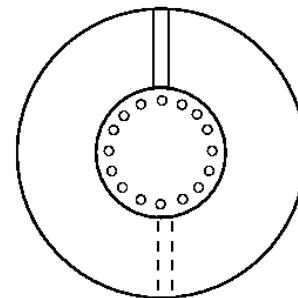
15 cm

Multi-channel Solenoid

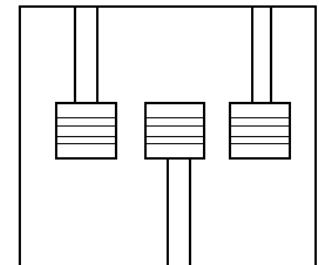
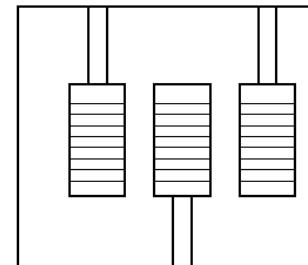
Beam	Ne^{1+}
Input energy	2 MeV, 0.1 MeV/u
Output energy	20 MeV, 1 MeV/u
Current	300 mA
Frequency	50 MHz
Length	8.6 m
Number of resonators	17
Voltage per gap	400-500 kV
Field in the solenoids	15 Tesla
Eff. Length of the solenoids	15 cm

Interdigital H-mode resonator configurations

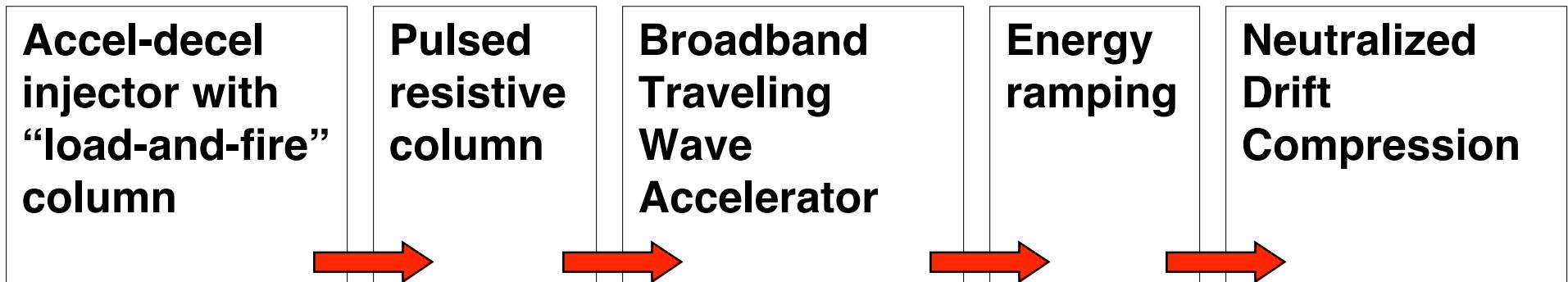
Ring Beam



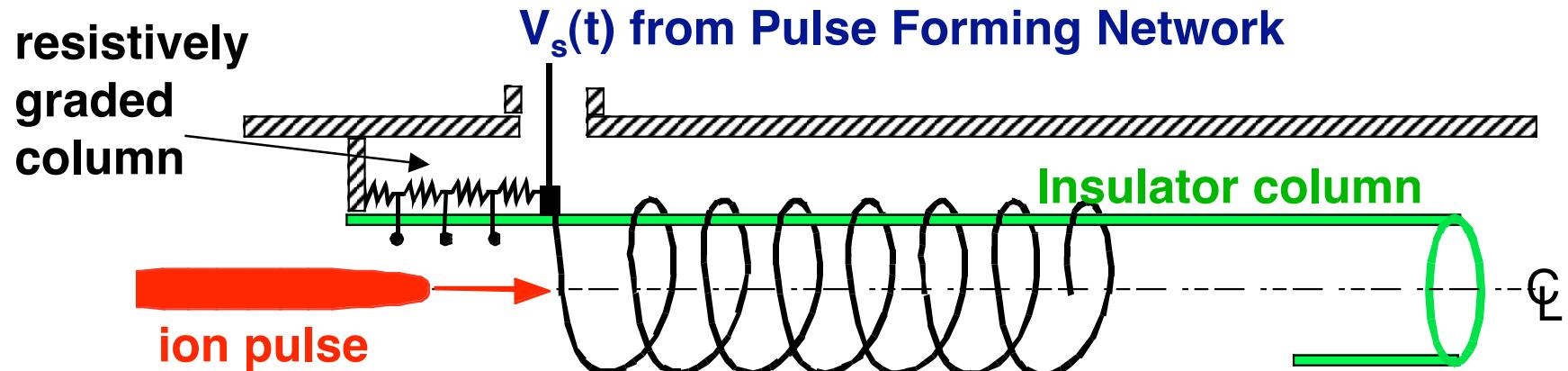
Planar Beam



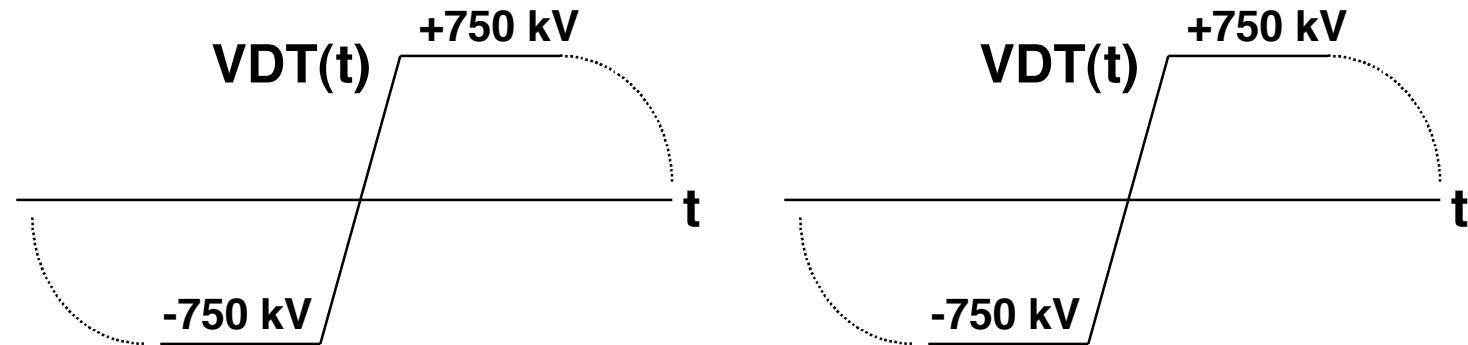
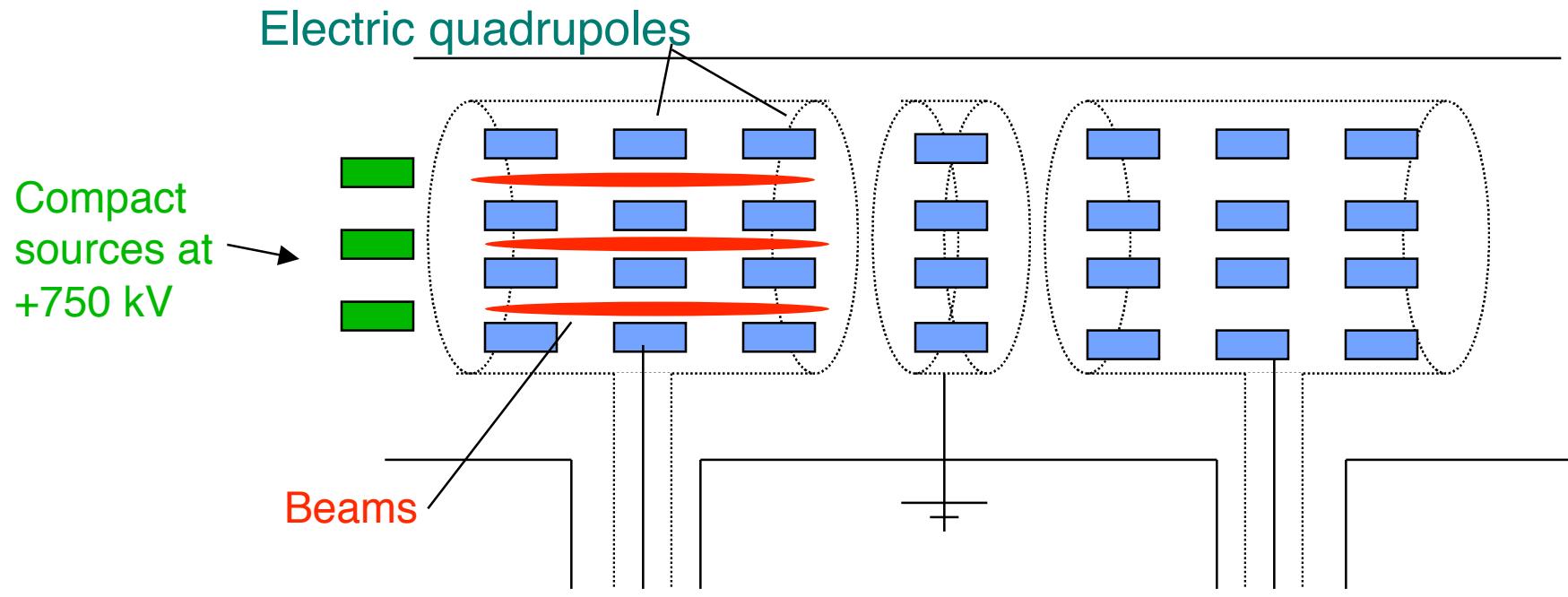
Concept (2a) for a Broadband Traveling Wave Accelerator



- Traveling Wave Accelerator is based on slow-wave structures (helices)
- Beam “surfs” on traveling pulse of E_z (moving at $\sim 0.01 c$ in first stage)
- *One possible configuration:*



Pulsed Drift Tube Linac (concept 2b) with internal electric quadrupoles



What are the main issues for final focus/drift compression?

accelerator issues

- switchyard or moving experiments
- time-dependent focusing
- interface between the accelerator and neutralized drift

focusing issues

- solenoid or quadrupole focusing
- charge-state spread
- adiabatic plasma lens

plasma issues

- beam-plasma interaction and stability
- dipole and quadrupole fields in plasmas
- atomic physics (stripping, charge exchange, energy loss)

system issues

- requirements on momentum tilt Δp_z and thermal spread δp_z
- beam combining
- flexibility of beam parameters

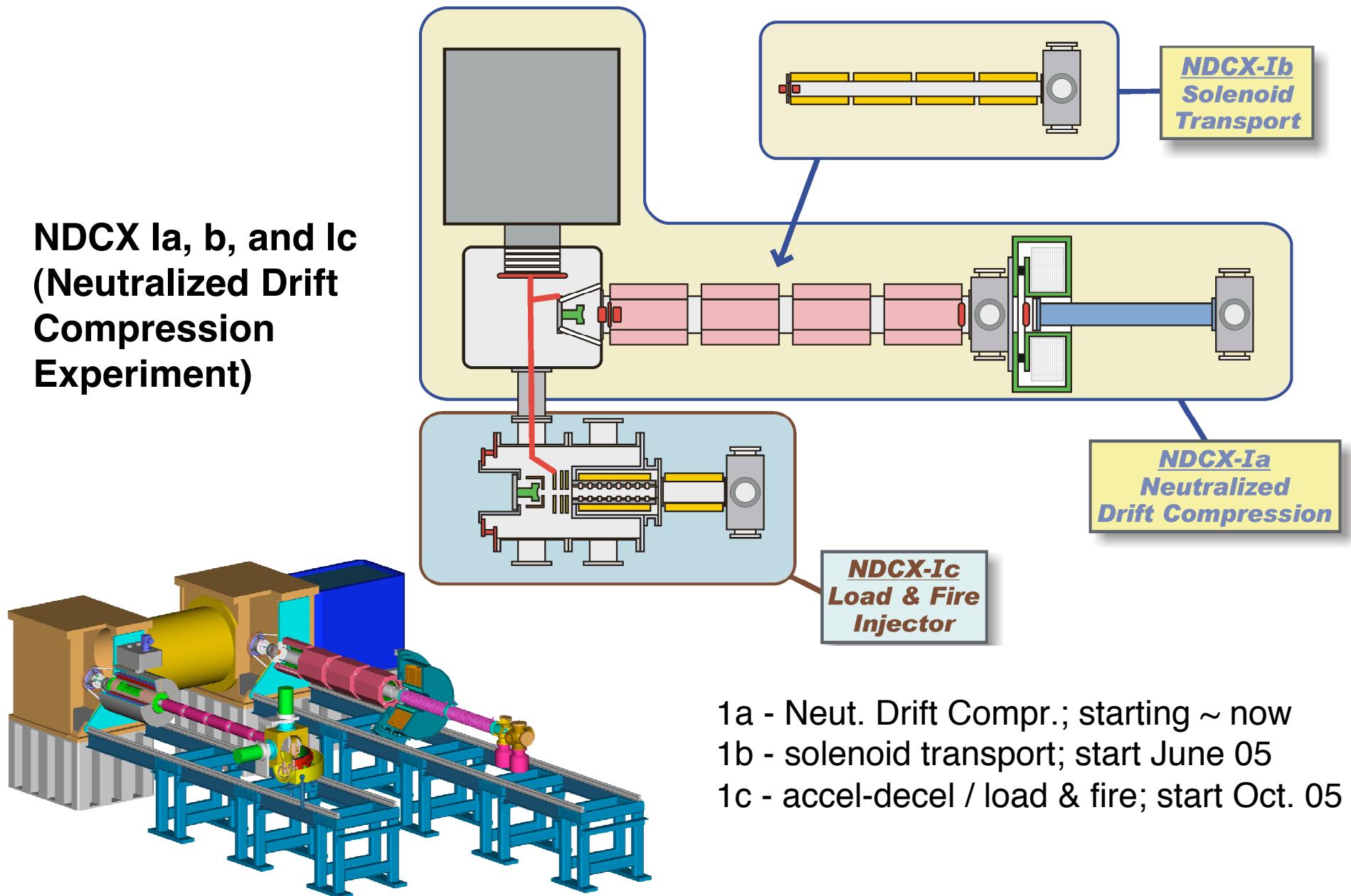
interface issues with accelerator

There are also a number of options and tools for compression and final focusing

- neutralized compression**
- large stationary solenoid lens for final focus**
- dipoles for: stopping electrons; switch yard; achromatic multibeam concept, but must work in plasmas**
- solenoid to suppress instabilities**
- pulsed lenses to compensate chromatic problems**
- adiabatic (funnel) lens for possible final factor of ~3 radial compression**
- large convergence angle to obtain small focal spot**



Near term experiments (over next ~2 years) investigate neutralized drift compression, solenoidal transport, and high α injection



Phase 2: 10 A, 100-ns He beam at end of accelerator

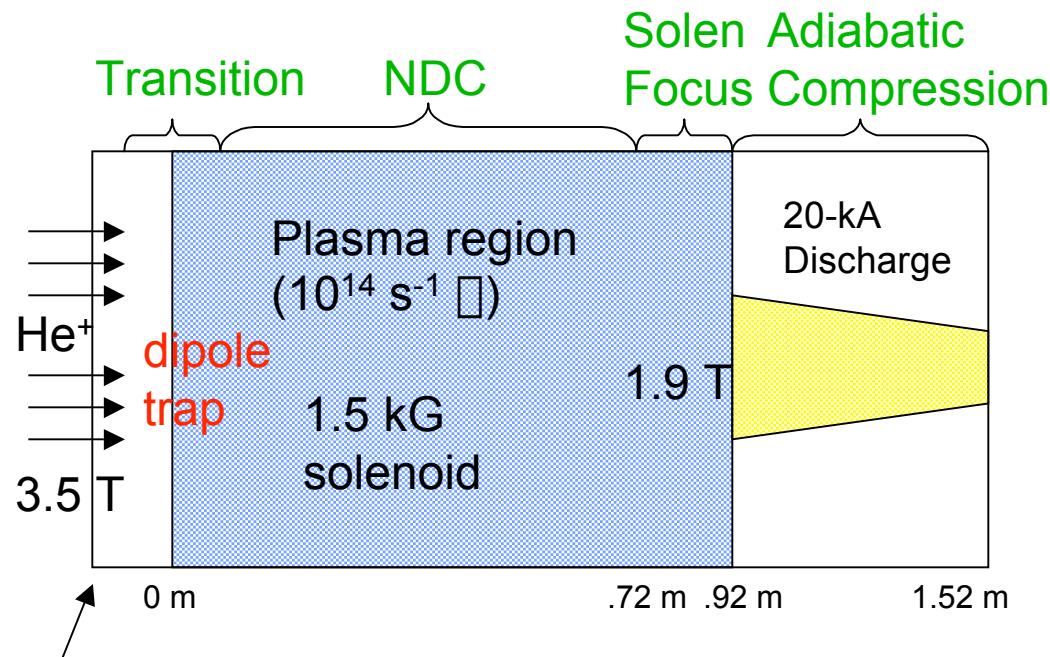
Compressed from 1-A 1- μ s beam in accel-decel injector

$\Delta F = 1.2 \mu\text{-mm-mrad}$, $r = 2\text{cm}$, .75 J

60-cm long adiabatic discharge channel (20 kA); 10 mm to 1 mm radius

67% energy tilt from 500-1000 keV in 100 ns

Need to compress 100x and focus to 1-mm spot to achieve “HEDP”



(slide courtesy D. Welch)

Vacuum, BF

The Heavy Ion Fusion Virtual National Laboratory

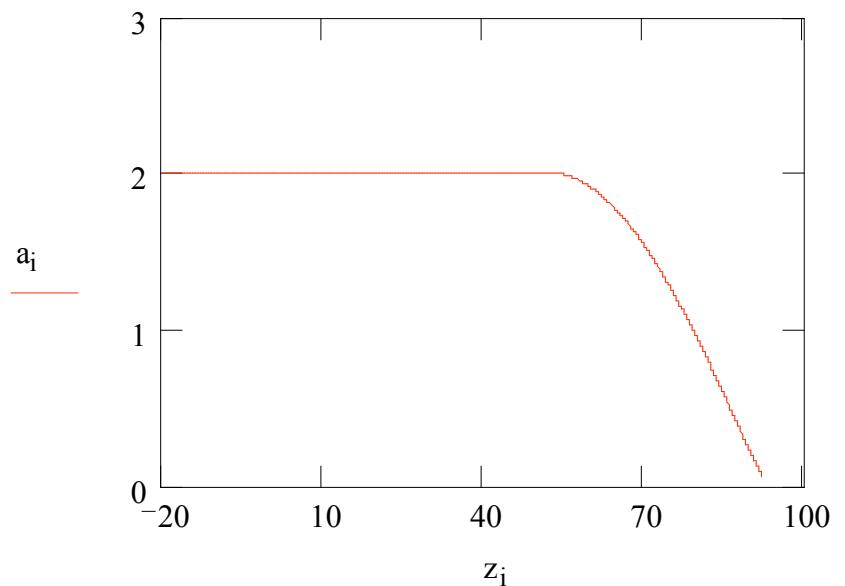
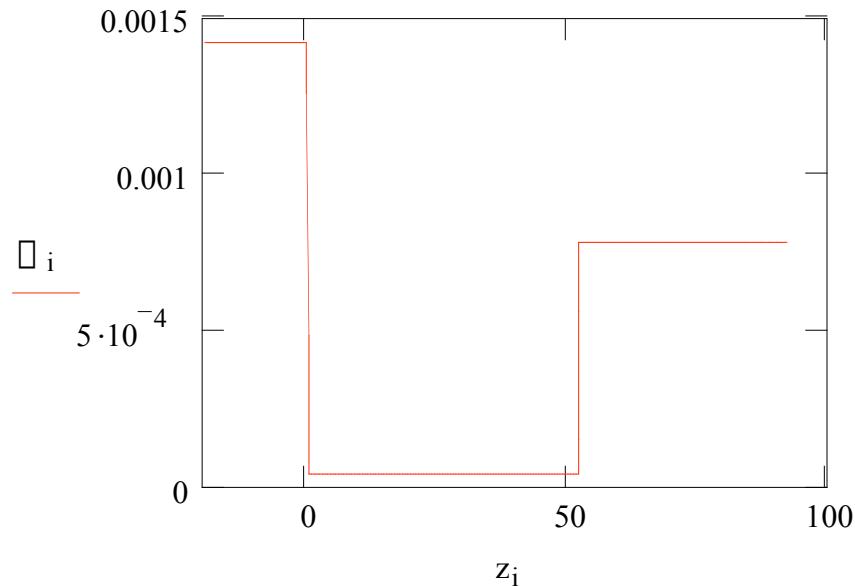


Envelope solution for Brillouin Flow and Neutralized Drift Compression

Solution for 750 keV He⁺

(slide courtesy D. Welch)

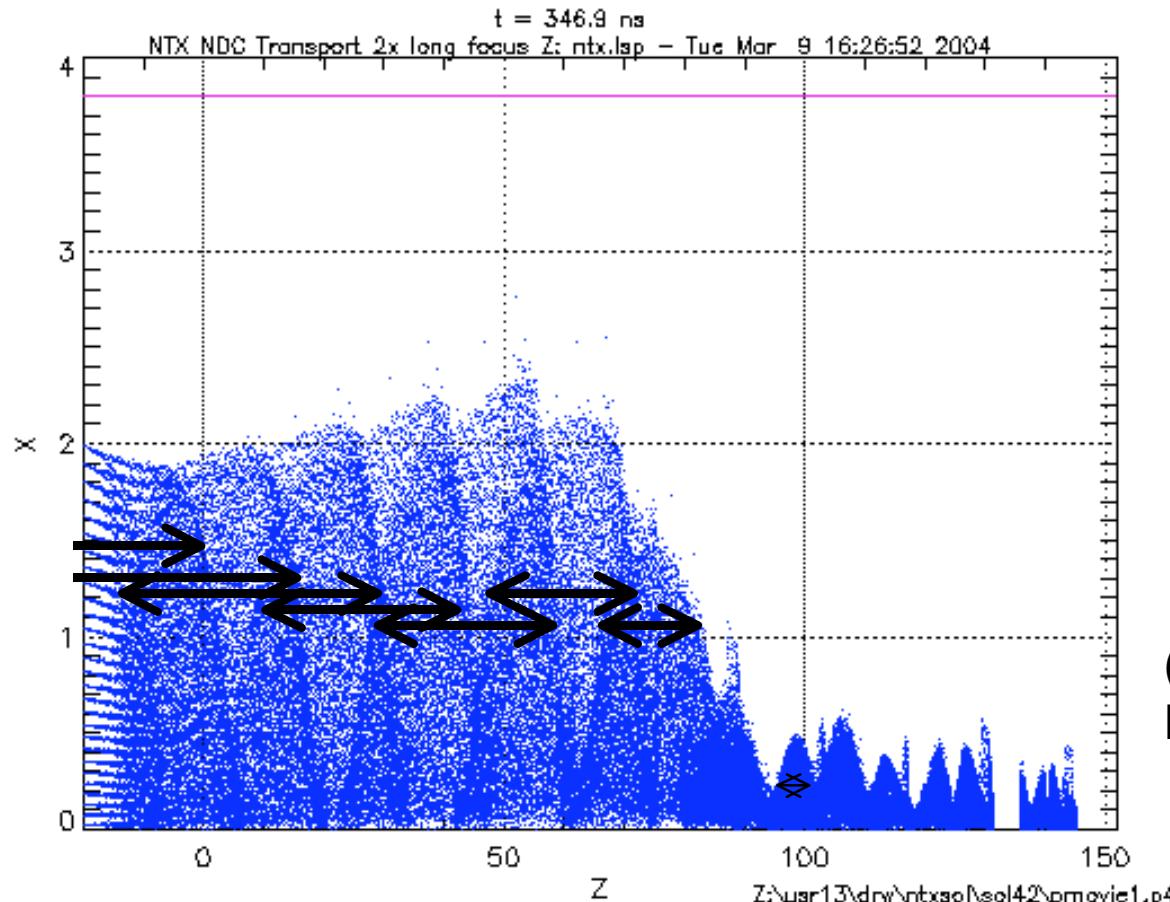
Long 1.9-T, 40 cm focusing coil at z = 52-92 cm



Snapshots of Beam Transport

Beam relaxes longitudinally due to incomplete neutralization

Longitudinal “overfocus” to $z = 139$ gave shortest pulse at $z = 152$



(slide courtesy
D. Welch)

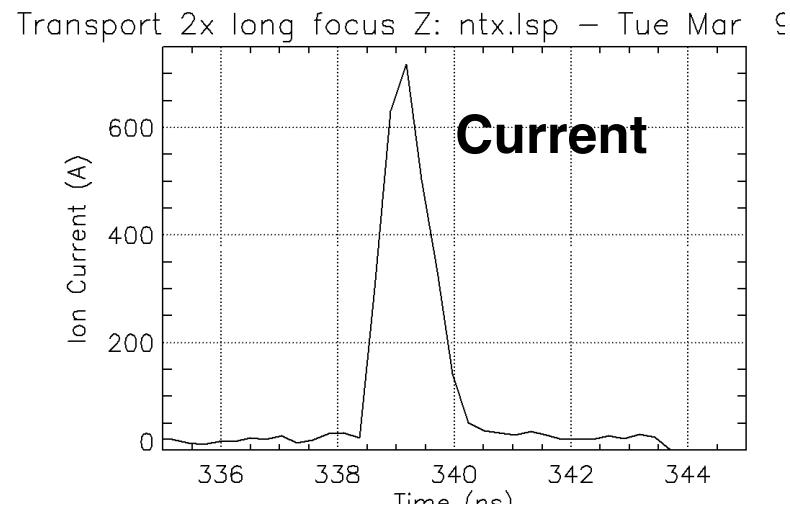
Possible to compensate for less than ideal neutralization

Beam compresses to WDM conditions

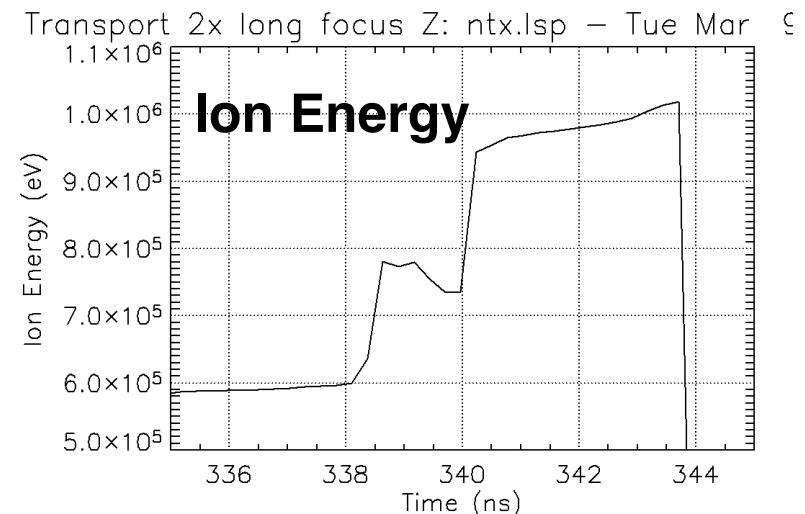
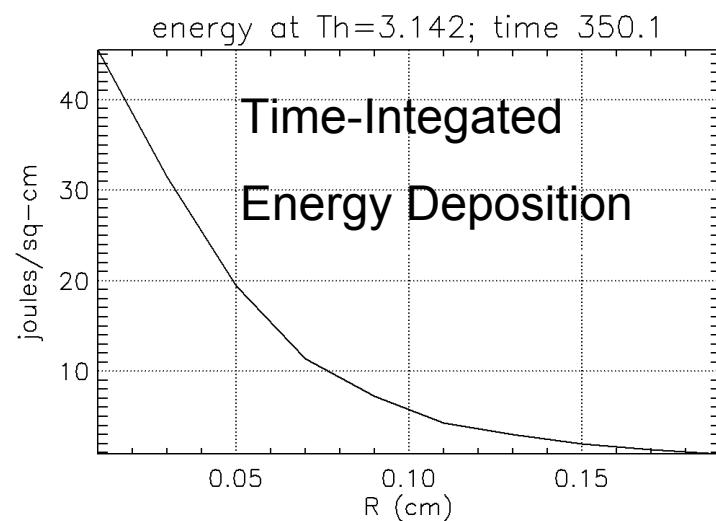
< 1 ns, < 1 mm pulse on target z = 152 cm

Compressed to .75 kA, 75x

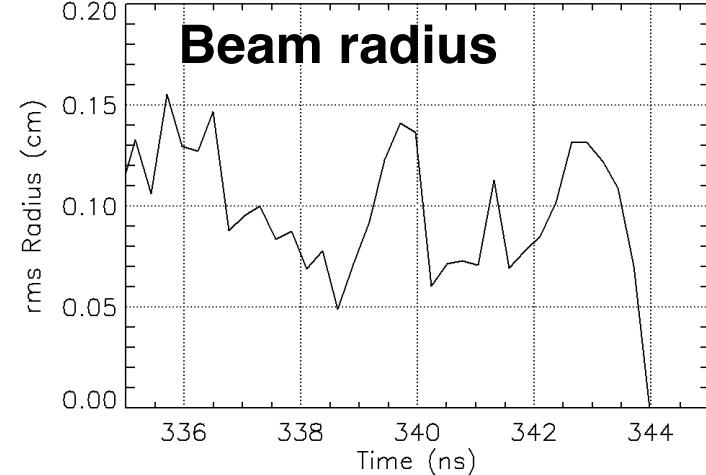
(slide courtesy D. Welch)



NTX NDC Transport 2x long focus Z: ntx.lsp – Tue Mar 9 16:55:55 2016



Transport 2x long focus Z: ntx.lsp – Tue Mar 9 16:55:55 2016



Conclusion

We are continuing to evaluate the best regime (i.e. target temperature, density, material and configuration) for accelerator-driven HEDP/WDM experiments

Neutralized drift compression and neutralized focusing system appear to be good match for requirements. The physics of beams (particularly propagating through neutralizing plasmas) is rich scientifically.

“Brainstorming” working group meetings and Accelerator Driven HEDP workshop at LBNL are examining wide range of accelerator architectures from rf to induction, from linacs to rings, are scoping out the best accelerator approach for HEDP/WDM studies